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Recent Progress in Computational Methods Development for Pebble Bed Physics and System Modeling

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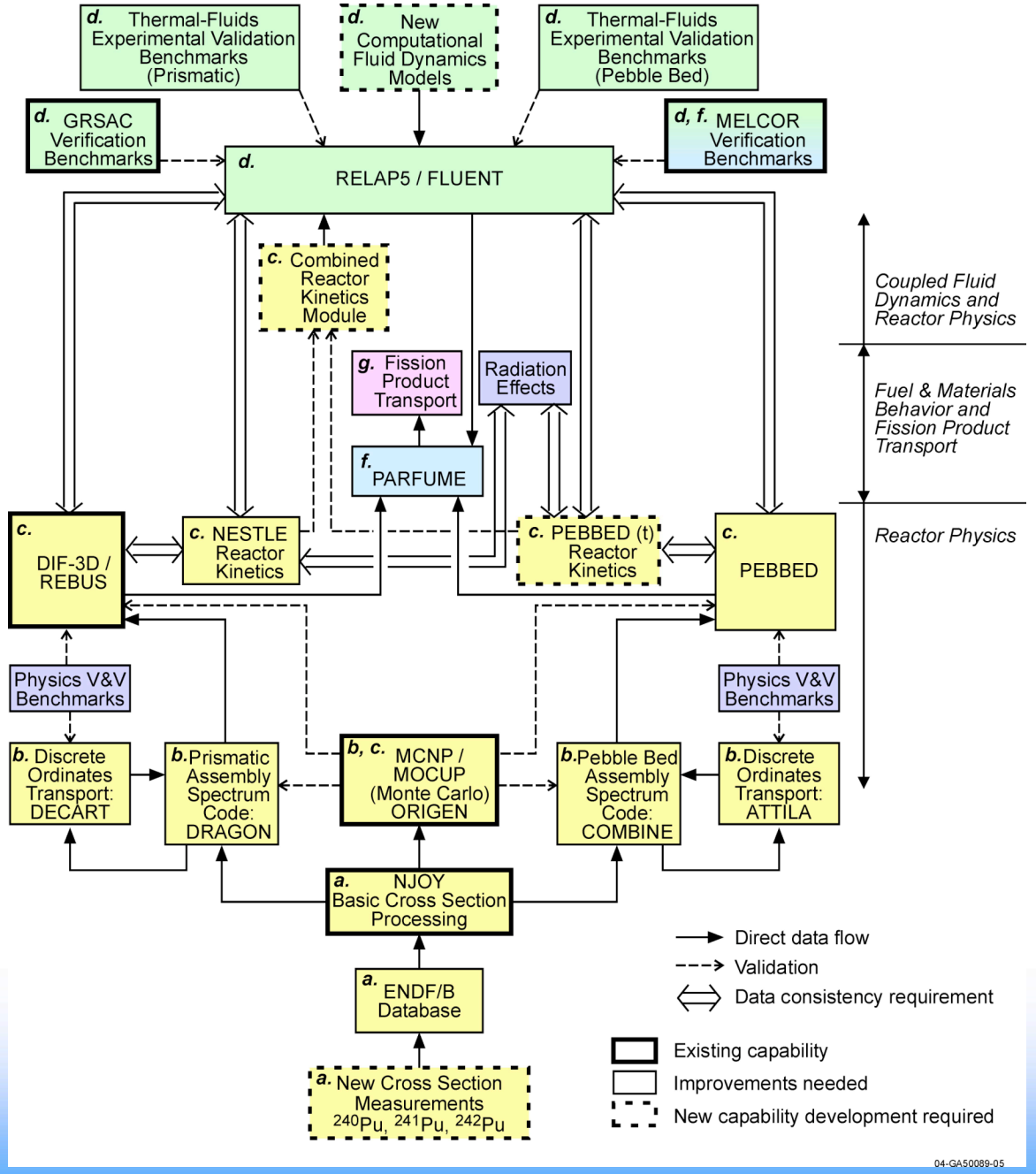
Proposed VHTR Code Suite



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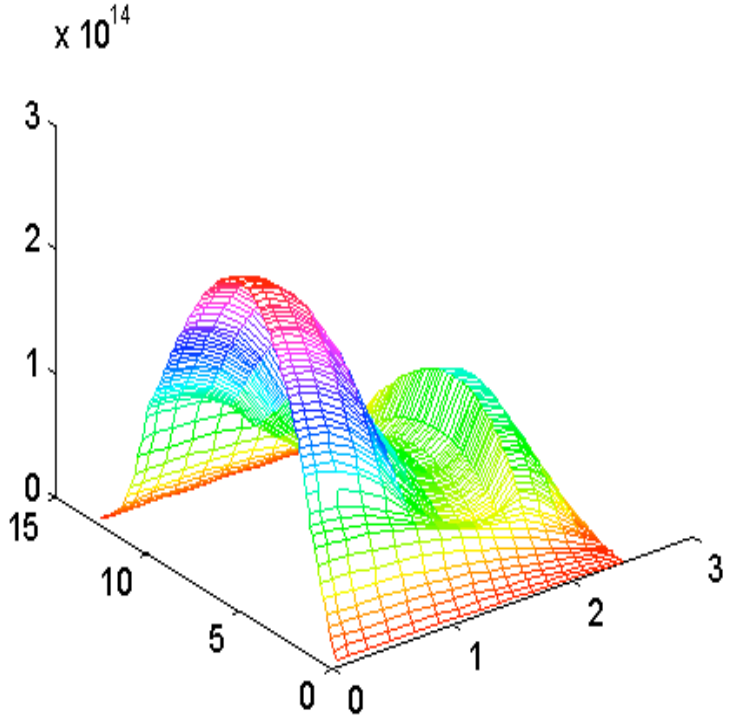
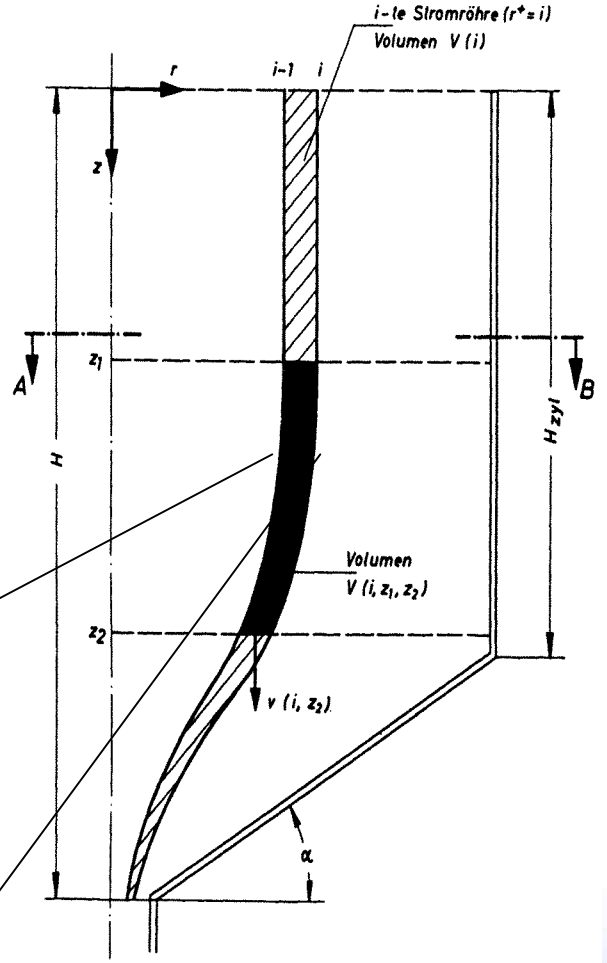
Pebble Bed Reactor Core Physics - Areas of Research and Development

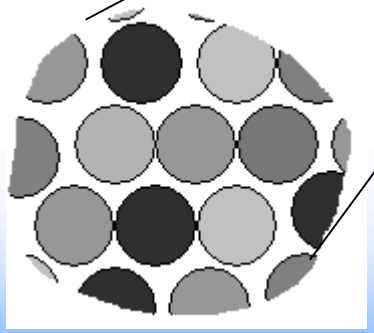
- PEBBED pebble bed reactor fuel cycle analysis code
- Coupled-Code Development and Cross-section Generation
- Material-Neutronics Interface



The PBR Fuel Management Problem

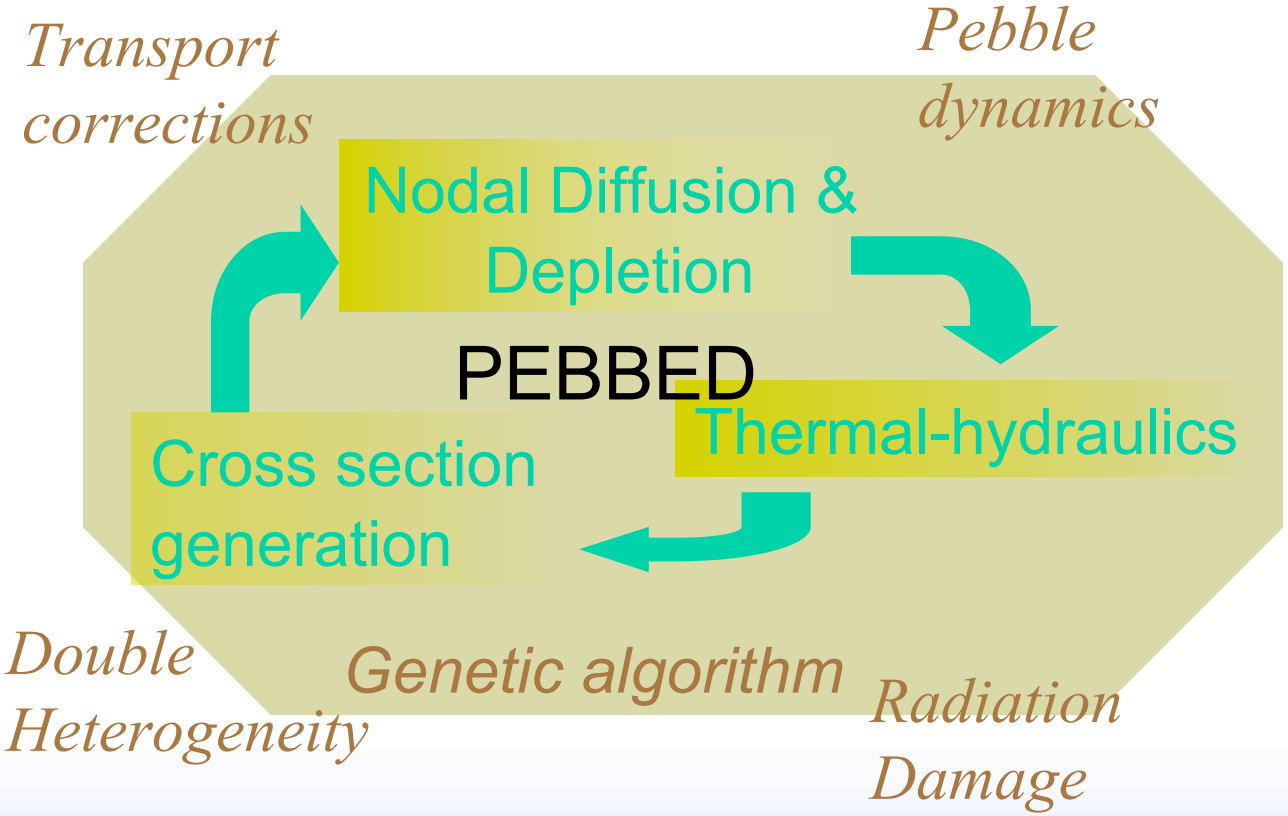
- Fuel flows along streamlines (deterministic component)
- Stochastic component leads to uncertainty
- Partially burned pebbles are recirculated until spent
- Long mean free path, high burnup, harder spectrum

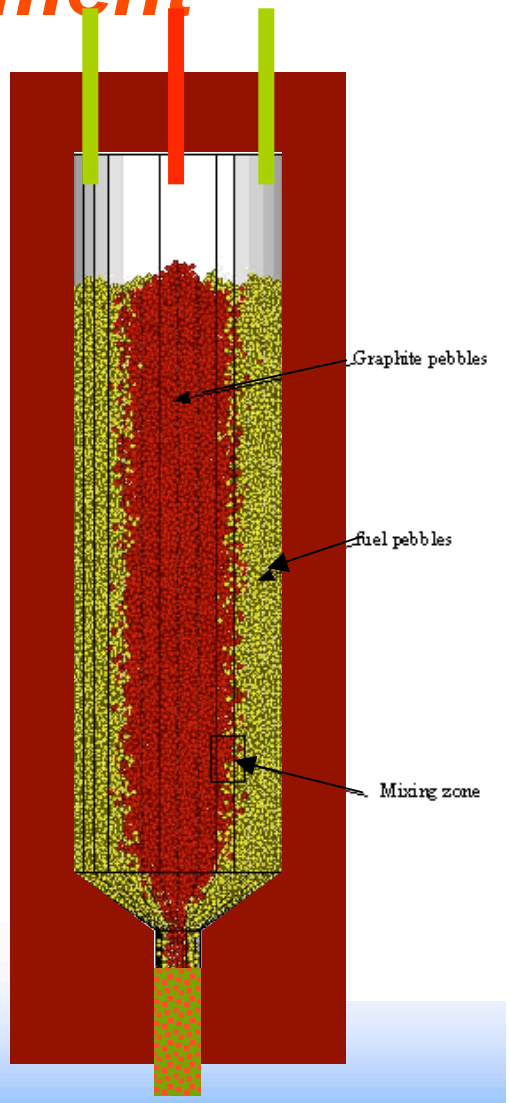




LWR methods & codes cannot easily be applied

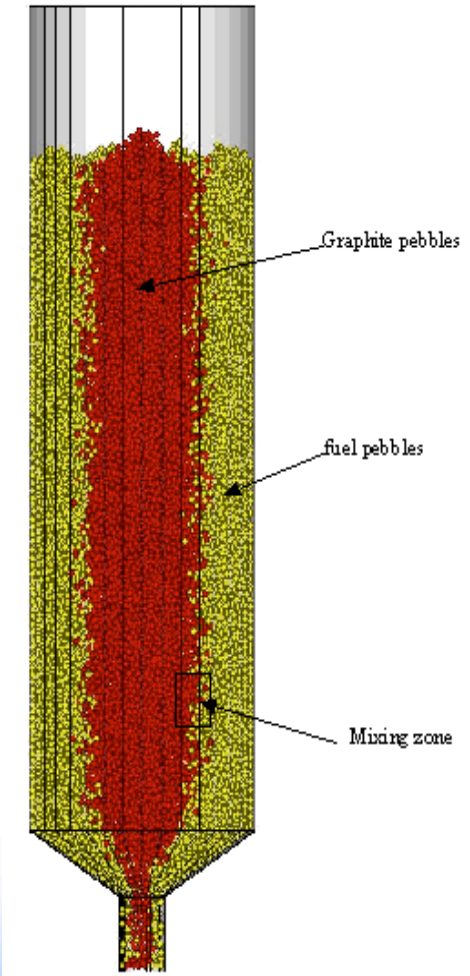
Pebble Bed Reactor Core Physics - Areas of Research and Development





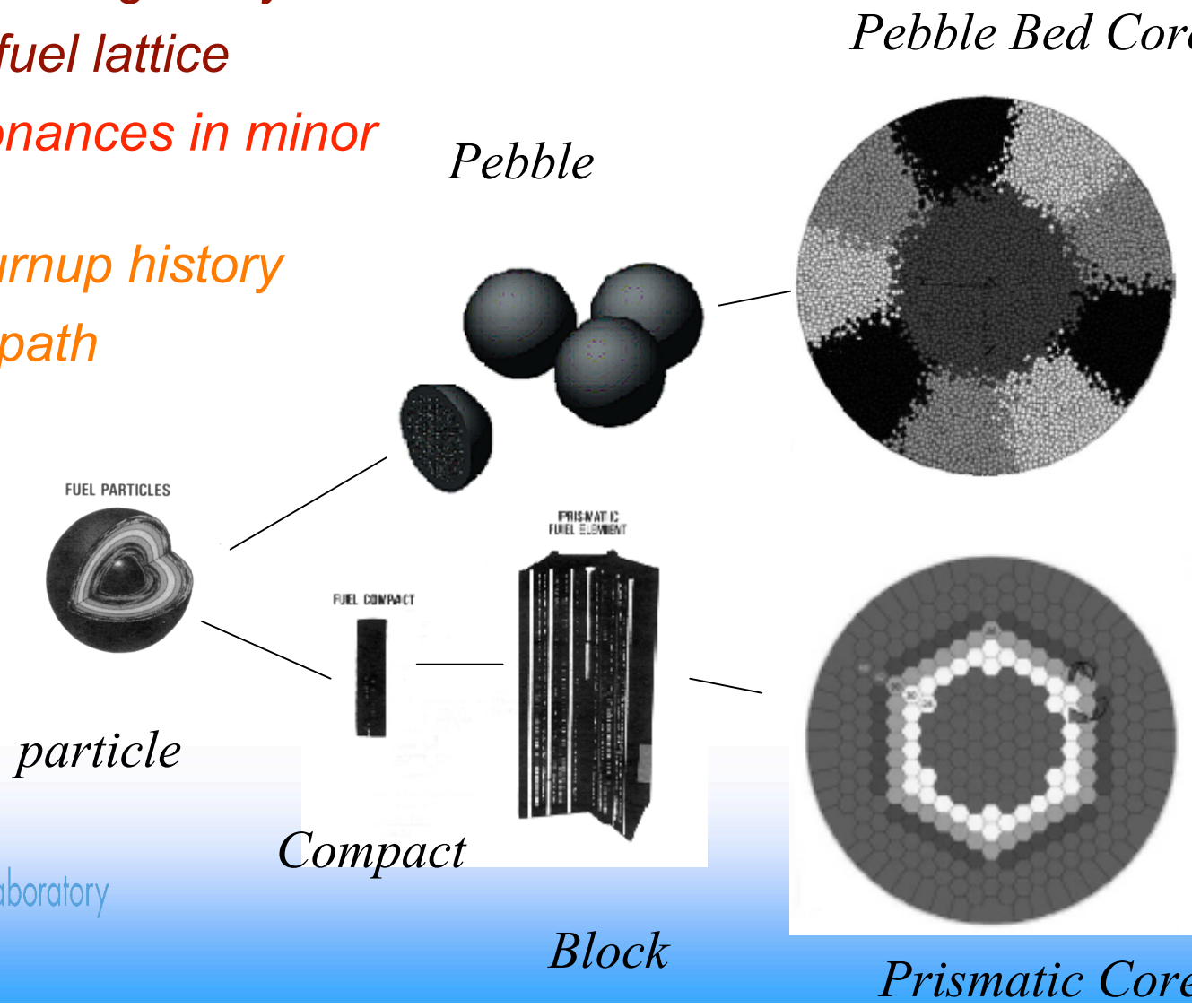
PEBBED

- Equilibrium Fuel Cycle Analysis of Pebble Bed Reactors
- Finite Difference or Nodal Diffusion
- Low-order thermal-hydraulic modules for normal and accident temperature estimation or THERMIX for accuracy
- Thermal cross section feedback via table lookup or direct calls to a spectrum module
- Arbitrary pebble recirculation schemes can be modeled
- Genetic Algorithm for core geometry and fuel loading optimization



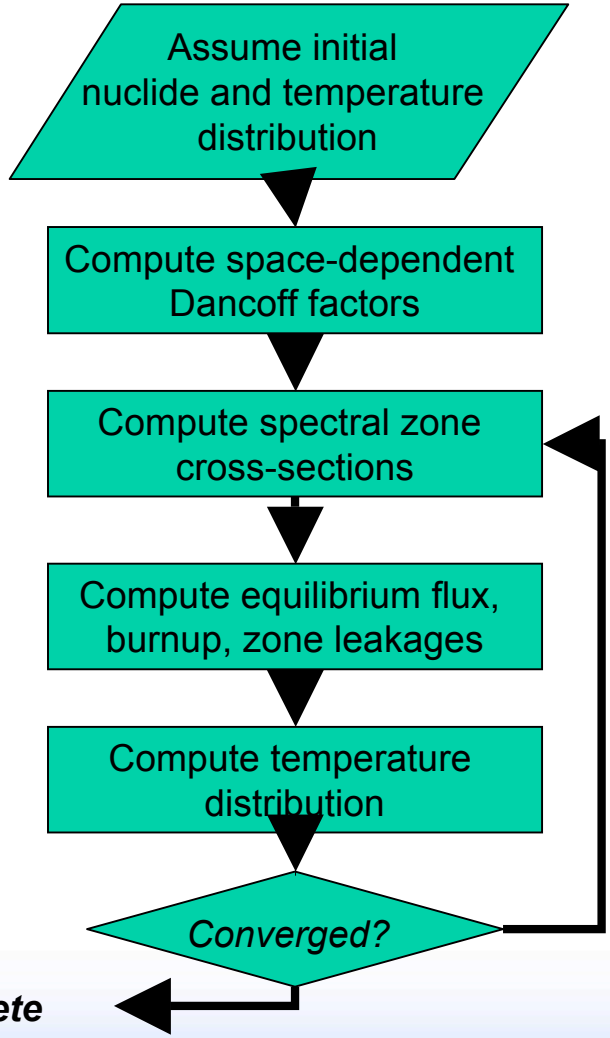
Cross sections for TRISO-based Fuel

- *2 or 3 levels of heterogeneity*
- *Randomness in fuel lattice*
- *Low-energy resonances in minor actinides*
- *Uncertainty in burnup history*
- *Long mean free path*



Current Efforts

- Development of Analytical Nodal Diffusion Solver
- Transport Corrections for non-diffusive regions
- Improved Cross-section generation with COMBINE
- Transient Analysis with NEM-THERMIX
- Computational Pebble Flow Dynamics
- Calculation of Displacement Threshold Energy/Neutronic Effects of Radiation Damage and Annealing



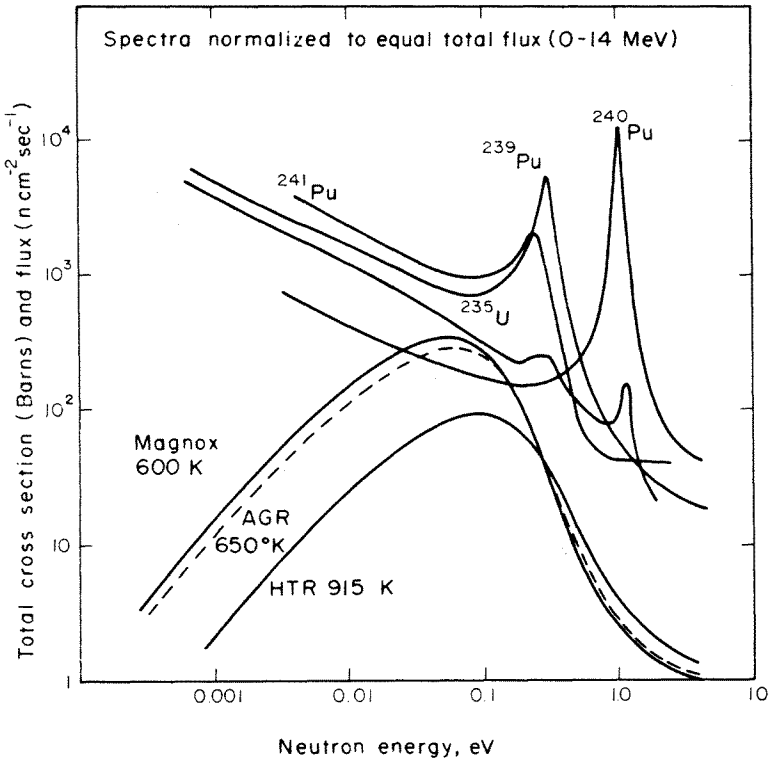
Integrated Cross-section Generation

COMBINE *(ENDF/B v6) Developments*

- Proper treatment of low energy resonances, energy dependent bucklings, quantum levels in resolved resonances, lumped fission parameters)
- Double-heterogeneity with a new method for computation of spatially-dependent Dancoff factors
- Efficient (on-line) coupling to PEBBED

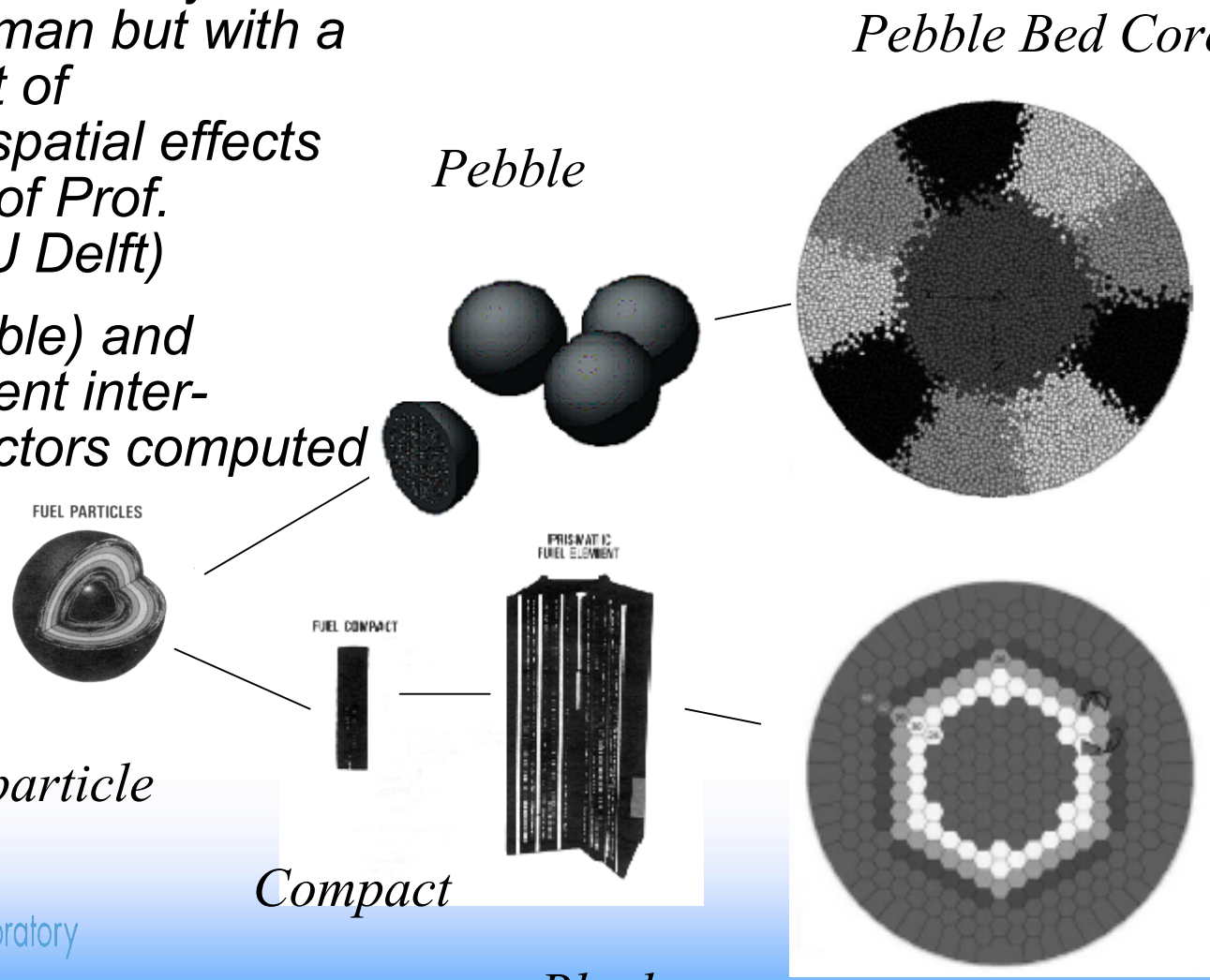
Outstanding Issues

- *Leakage effect between nodes*
- *Proper generation of cross sections in non-multiplying media (reflectors, voids)*



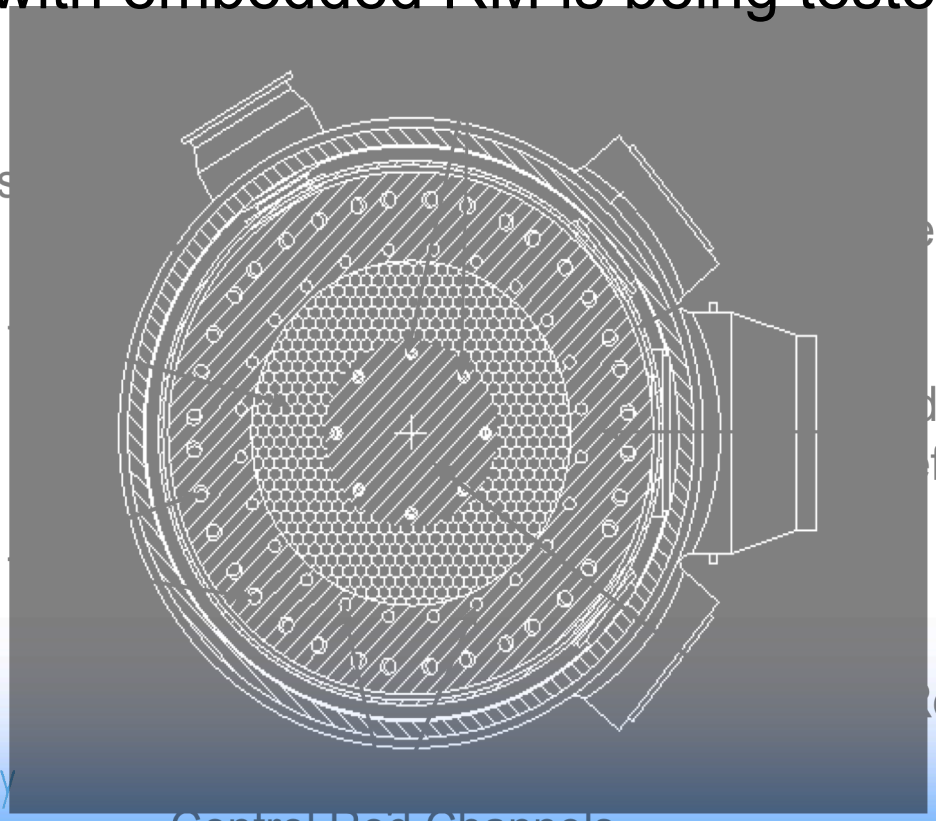
Dancoff Factors for VHTR Fuel

- *Builds on previous work by Bende & Kloosterman but with a rigorous treatment of randomness and spatial effects (with cooperation of Prof. Kloosterman of TU Delft)*
- *Particle (intra-pebble) and geometry-dependent inter-pebble Dancoff factors computed*



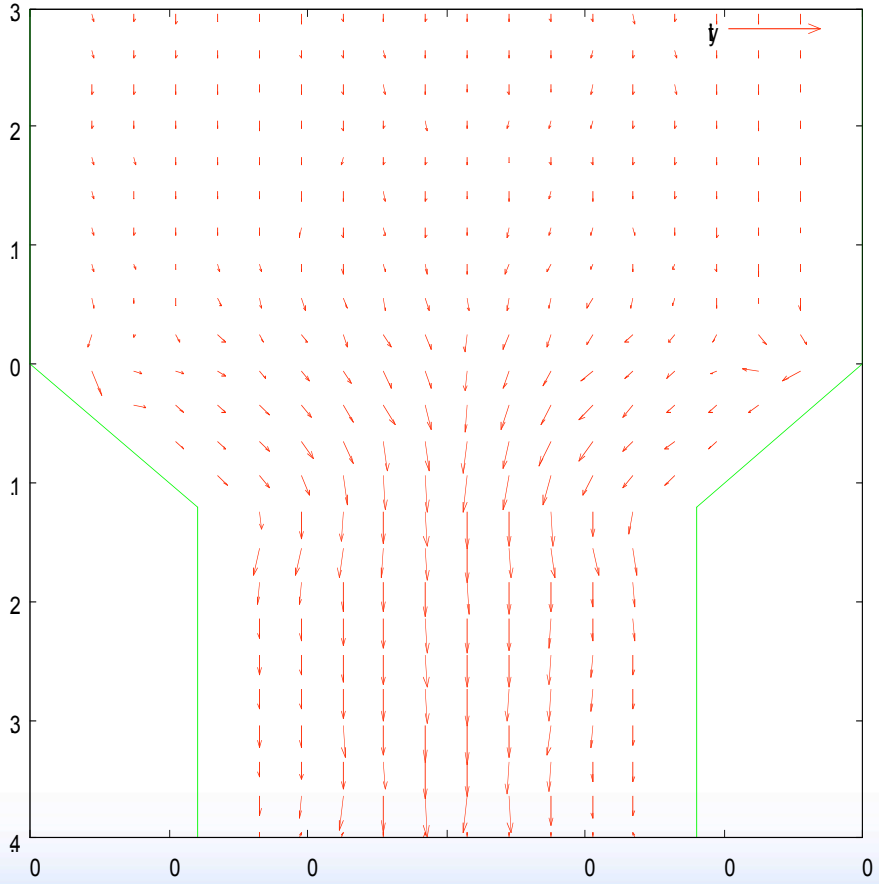
Integrated transport treatment for non-diffusive nodes

- Response Matrix (transport) approach under investigation (*Georgia Institute of Technology*)
- Preliminary results look promising – an RZ transient diffusion solver with embedded RM is being tested

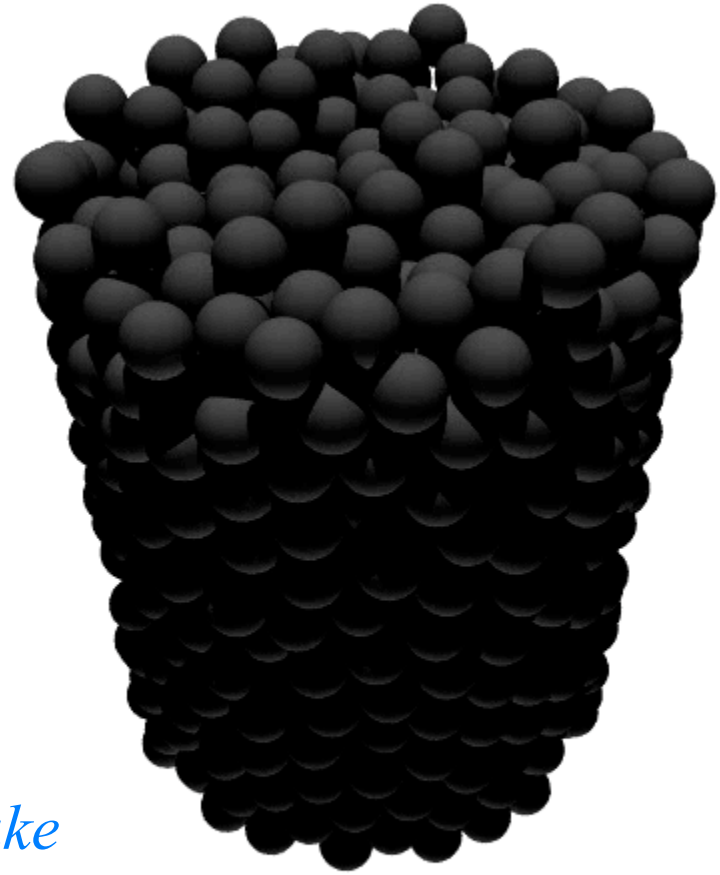


Pebble Flow Simulation

- *Hard particle dynamics simulation of core loading and settling*
- *Variable packing fraction and pebble flow simulated but not validated for graphite*
- *Dynamics of pebble flow to drive time-dependent fuel loading analysis capability (Approach to Asymptotic)*
- *Experimental validation and determination of parameters are needed*

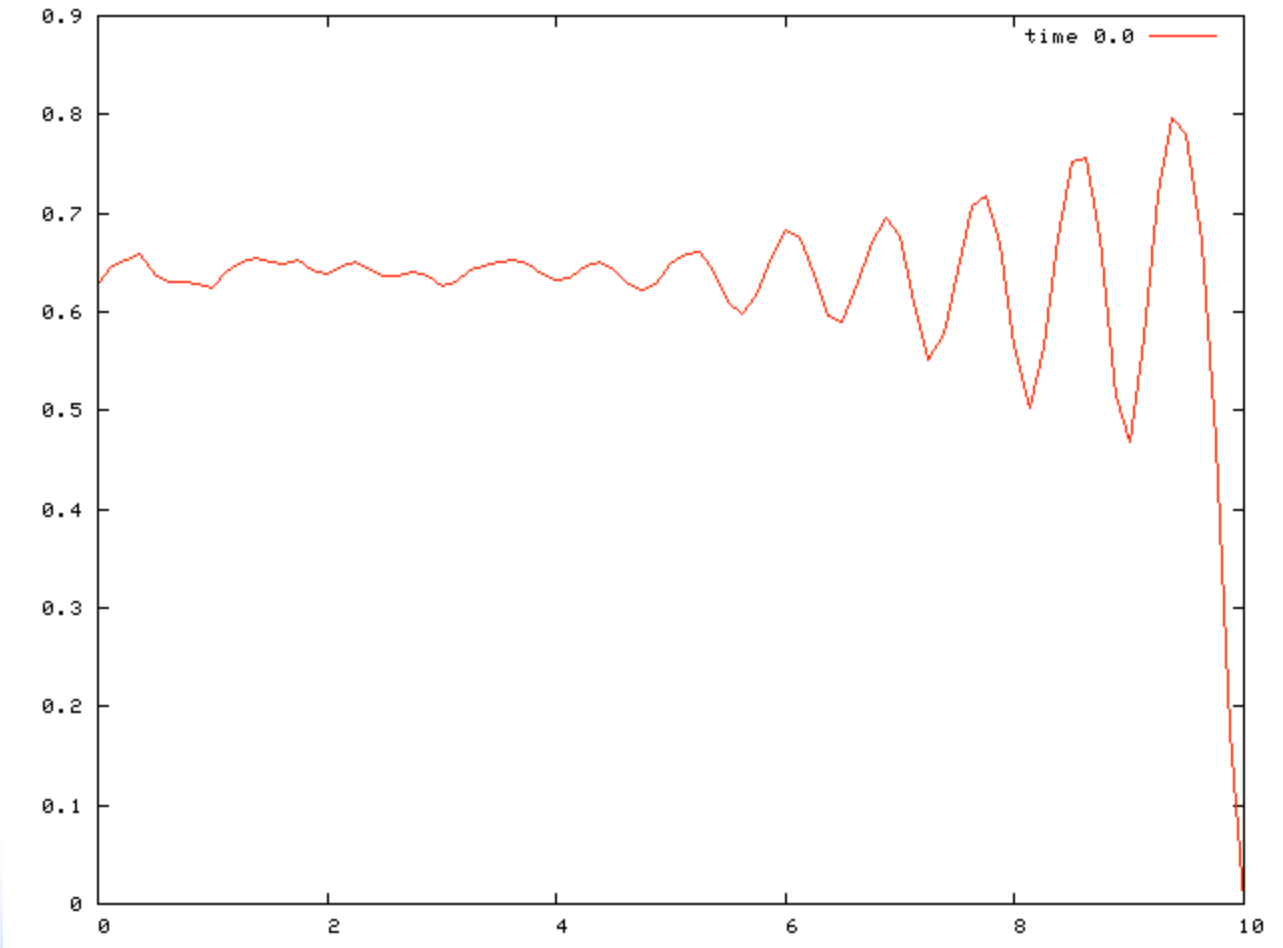


Pebble Settling during a Seismic Event



1000 pebbles in vat
Mercalli X horizontal quake

Pebble Settling during a Seismic Event



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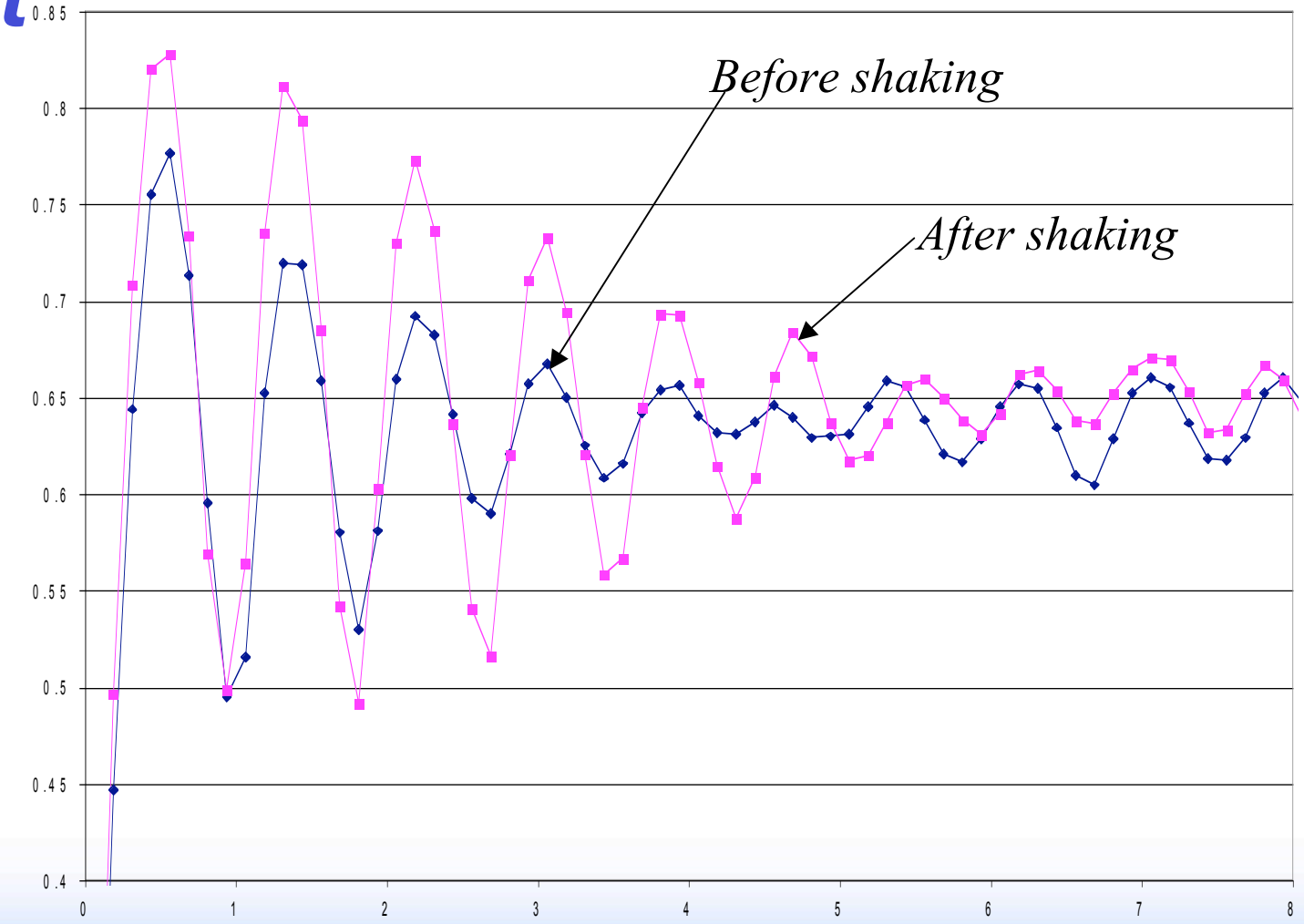


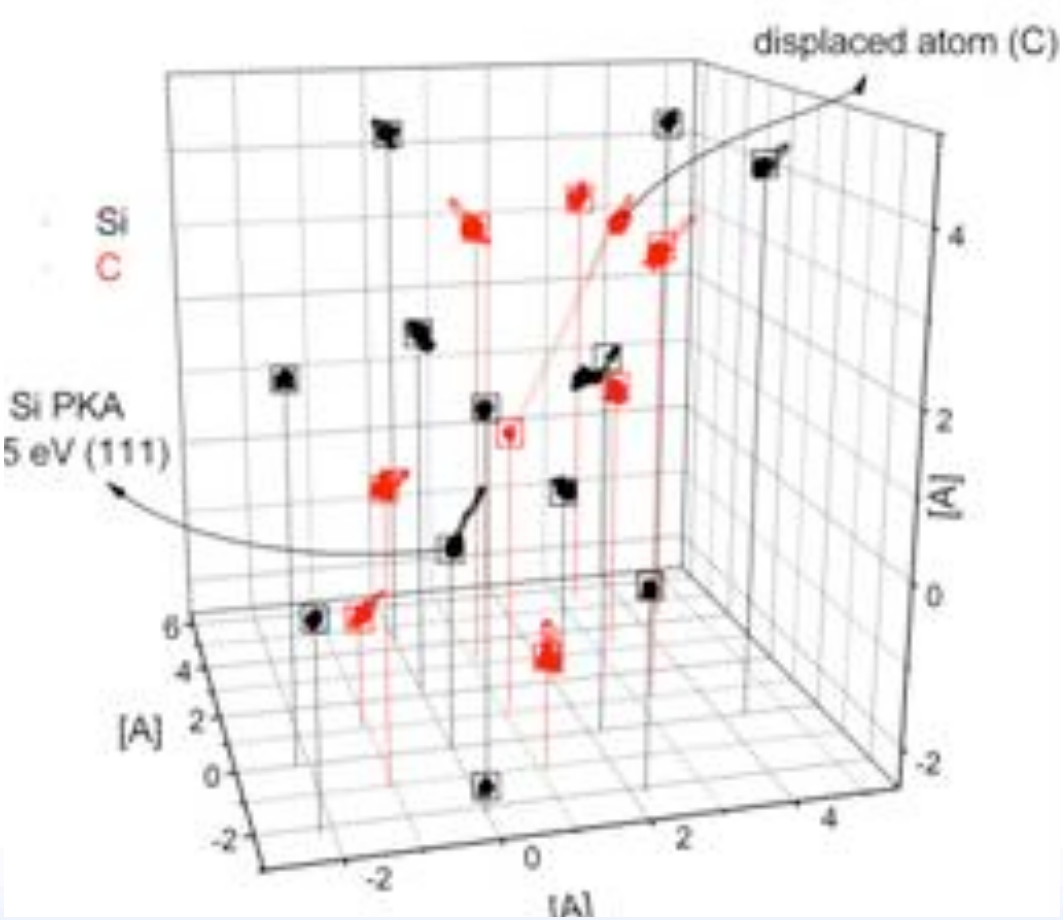
Material-Neutronics Interface – modeling radiation damage and its effects on core dynamics

- Molecular dynamic simulation of radiation damage in graphite and SiC
- Calculation of scattering cross sections in damaged crystals
- Calculation of threshold energy and displacement kerma cross sections at prototypical temperatures
- Modeling of damage to assess effects of annealing on transient behavior (thermal conductivity recovery – thermal scattering law changes)

$$E = \frac{1}{2}\sum_{i \neq j}\left\{ f_c(r_{ij})\left[f_R(r_{ij}) + b_{ij}\ f_A(r_{ij}) \right] \right\}$$

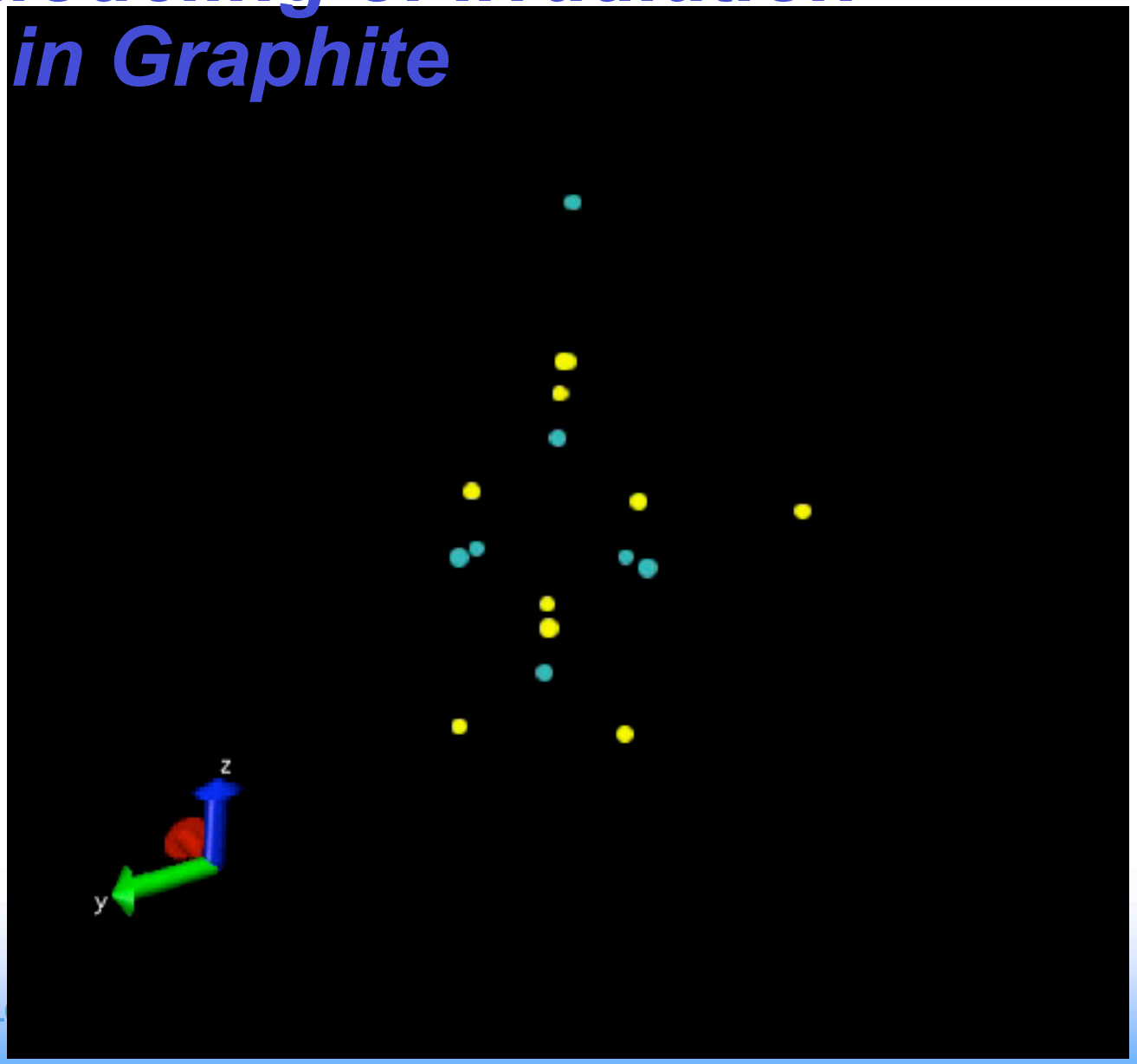
$$f_c(r_{ij}) = \begin{cases} 1 & , r_{ij} < R_{ij} \\ \frac{1}{2}\left\{ 1 + \cos\left[\pi \frac{(r_{ij} - R_{ij})}{(S_{ij} - R_{ij})} \right] \right\} & , R_{ij} < r_{ij} < S_{ij} \\ 0 & , S_{ij} < r_{ij} \end{cases}$$

Dynamic modeling of radiation damage



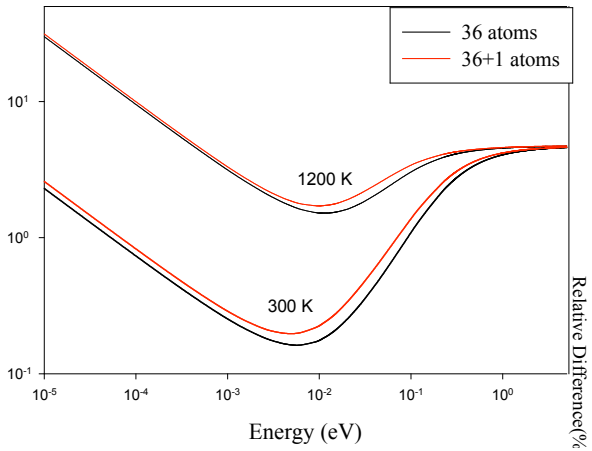
MDCASK model of atomic movement in SiC

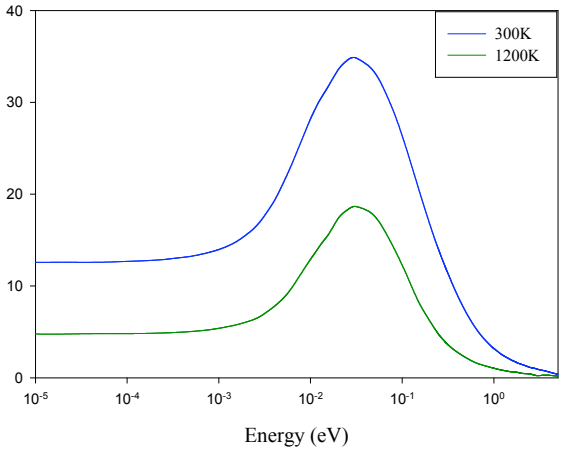
Kinetic Modeling of Irradiation Damage in Graphite



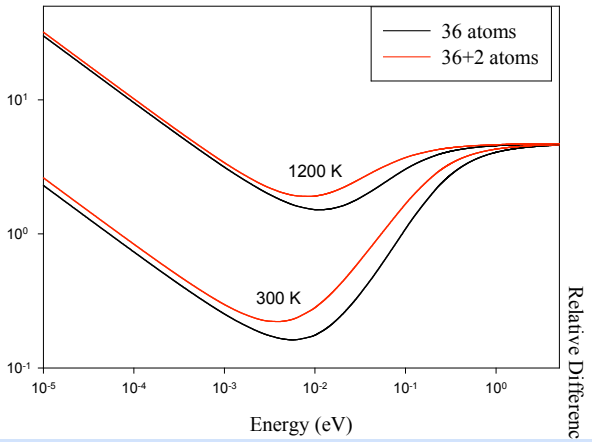
Effect of radiation damage on scattering cross section

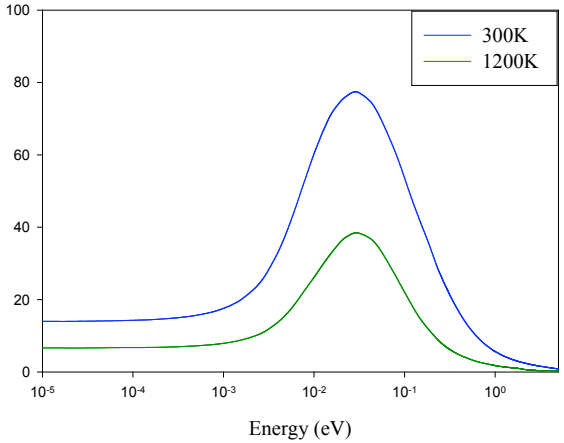
1 interstitial atom





2 interstitial atoms





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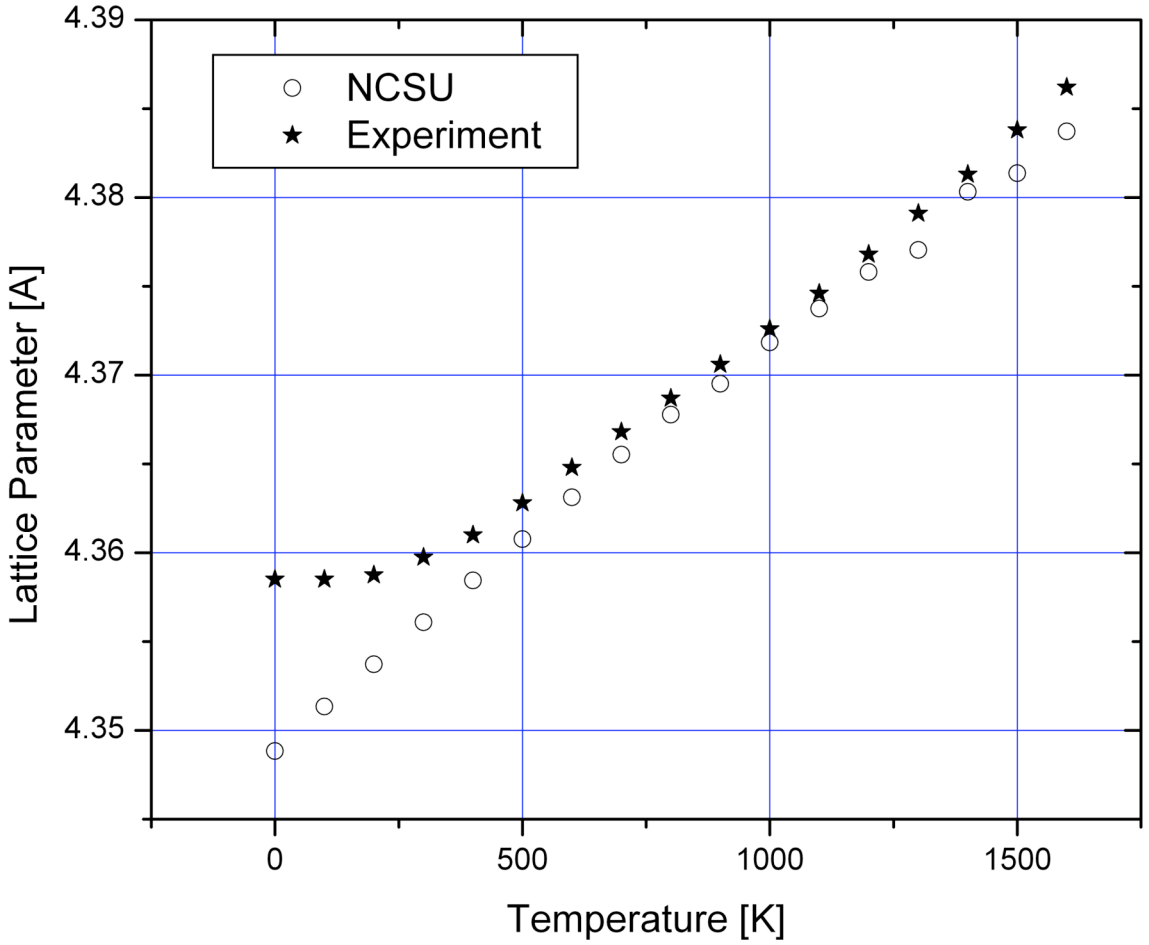
Thermal inelastic scattering cross section (b)

Relative Difference (%)

Prediction of lattice parameters



Summary

- PEBBED for state-of-the-art PBR analysis and design
  - Advanced optimization
  - Nodal Diffusion
- Coupled-Code Development and Implementation
  - NEM-THERMIX (thermal)
  - COMBINE (cross sections)
- Radiation effects on Core Dynamics
- 2006 – Validation and benchmarking of results